# Measurement of the ratio of branching fractions and difference in CP asymmetries of thedecays B+ -> J/psi pi(+) and B+ -> J/psi K+

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# Measurement of the ratio of branching fractions and difference in CP asymmetries of the decays $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$

## The LHCb collaboration

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Abstract: The ratio of branching fractions and the difference in *CP* asymmetries of the decays $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ are measured using a data sample of *pp* collisions collected by the LHCb experiment, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$ at centre-of-mass energies of 7 and 8 TeV. The results are

$$\frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = (3.83 \pm 0.03 \pm 0.03) \times 10^{-2}\,,$$

$$\mathcal{A}^{\text{CP}}(B^+ \to J/\psi\pi^+) - \mathcal{A}^{\text{CP}}(B^+ \to J/\psi K^+) = (1.82 \pm 0.86 \pm 0.14) \times 10^{-2},$$

where the first uncertainties are statistical and the second are systematic. Combining this result with a recent LHCb measurement of $\mathcal{A}^{\text{CP}}(B^+ \to J/\psi K^+)$ provides the most precise estimate to date of *CP* violation in the decay $B^+ \to J/\psi\pi^+$,

$$\mathcal{A}^{\text{CP}}(B^+ \to J/\psi\pi^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}.$$

Keywords: B physics, Branching fraction, CP violation, Hadron-Hadron scattering (experiments)

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## Contents



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## 1 Introduction

In the Standard Model, the decay $B^+ \to J/\psi K^+$ proceeds via a $b \to c\bar{c}s$ quark transition[1] and, since this process is dominated by a Cabibbo-favoured tree diagram, it is expected to exhibit negligible *CP* violation [1]. By contrast, for the decay $B^+ \to J/\psi \pi^+$, which proceeds via $b \to c\bar{c}d$, *CP* violation up to the percent level can be generated by interference between the suppressed tree-level diagram and additional gluonic penguin (loop) diagrams as shown in figure 1. Measurements of the branching fraction and *CP* asymmetry of the decay $B^+ \to J/\psi \pi^+$ can provide information about the size of the penguin-diagram contributions relative to that of the tree diagram. This is critical for estimating the effects of penguin-diagram contributions in $b \to c\bar{c}s$ decays on the determination of the *CP* violation parameter $\sin 2\beta$ [2, 3].

The world average of the branching fraction $\mathcal{B}(B^+ \to J/\psi \pi^+)$ is $(4.1 \pm 0.4) \times 10^{-4}$ [4], with no significant *CP* asymmetry observed so far. The world average value of $\mathcal{A}^{\rm CP}$ $(B^+ \to J/\psi \pi^+)$, which includes measurements from Belle, BaBar, D0 and LHCb [5–8], is $(1.0 \pm 2.8) \times 10^{-2}$ [4].

In an earlier analysis of a sample of $pp$ collision data corresponding to an integrated luminosity of $0.37\,\text{fb}^{-1}$ [8], LHCb measured the *CP* asymmetry $\mathcal{A}^{\rm CP}(B^+ \to J/\psi \pi^+) = (0.5 \pm 2.7 \pm 1.1) \times 10^{-2}$, as well as the ratio of branching fractions

$$\mathcal{R}_{\pi/K} \equiv \frac{\mathcal{B}(B^+ \to J/\psi \pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = (3.83 \pm 0.11 \pm 0.07) \times 10^{-2}. \tag{1.1}$$

[1] Unless otherwise specified, the inclusion of charge-conjugate processes is implied throughout this paper.

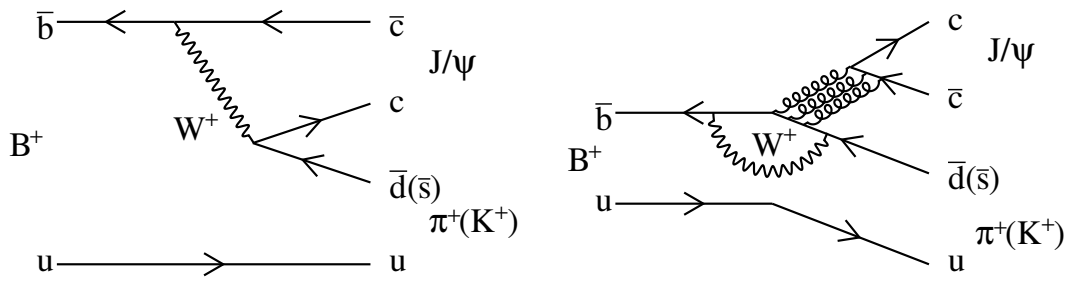


**Figure 1**. Feynman diagrams for $B^+ \to J/\psi\pi^+(K^+)$ decays at the tree (left) and one-loop (right) levels.

This paper reports an update of the analysis and uses the full $pp$ data sample from the LHC Run 1, corresponding to $1\,\text{fb}^{-1}$ collected at a centre-of-mass energy of $7\,TeV$ and $2\,\text{fb}^{-1}$ at 8 TeV, and measures $\mathcal{R}_{\pi/K}$ and $\Delta\mathcal{A}^{\text{CP}} \equiv \mathcal{A}^{\text{CP}}(B^+ \to J/\psi\pi^+) - \mathcal{A}^{\text{CP}}(B^+ \to J/\psi K^+)$, where these two decays are reconstructed using the dimuon decay mode of the $J/\psi$ meson. The result for $\Delta\mathcal{A}^{\text{CP}}$ is combined with the $\mathcal{A}^{\text{CP}}(B^+ \to J/\psi K^+)$ measurement from another LHCb analysis [9] to obtain $\mathcal{A}^{\text{CP}}(B^+ \to J/\psi\pi^+)$.

## 2 Detector and simulation

The LHCb detector [10, 11] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/$c$. The minimum distance of a track to a primary vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_{\text{T}})\,\mu\text{m}$, where $p_{\text{T}}$ is the component of the momentum transverse to the beam, in GeV/$c$. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The online event selection is performed by a trigger [12], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

In this analysis, the hardware trigger decision is required to be caused by at least one high-$p_{\text{T}}$ track that is consistent with being a muon. In the software trigger, two well-reconstructed muons with opposite charge are required to form a good-quality vertex and to have an invariant mass consistent with that of the $J/\psi$ meson [4]. The trigger also



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requires a significant displacement between the $J/\psi$ vertex and the associated PV of the $pp$ collision.

In the simulation, $pp$ collisions are generated using Pythia [13, 14] with a specific LHCb configuration [15]. Decays of hadronic particles are described by EvtGen [16], in which final-state radiation is generated using Photos [17]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [18, 19] as described in ref. [20].

## 3 Event selection

The same criteria are used to select $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ decays, except for those related to the identification of the final-state hadrons, and consist of a loose preselection followed by a multivariate selection. In the preselection, all three final-state tracks are required to be of good quality and within a fiducial region of the detector acceptance that excludes areas with large asymmetries in the detection efficiencies.

The $J/\psi$ candidates are formed from two oppositely charged particles with $p_{\rm T}$ greater than 550 MeV/$c$, identified as muons and consistent with originating from a common vertex but inconsistent with originating from any PV. The invariant mass of the $\mu^+\mu^-$ pair is required to be within $^{+43}_{-48}$ MeV/$c^2$ of the known $J/\psi$ mass [4], then constrained to that value in subsequent stages of the reconstruction. The $B^+$ candidates are formed by combining each $J/\psi$ candidate with a hadron candidate that has $p_{\rm T}$ greater than 1 GeV/$c$ and $p$ greater than 5 GeV/$c$ and forms a common vertex with the $J/\psi$. Both the kaon and pion mass hypotheses of the hadron candidates are kept. Each reconstructed $B^+$ candidate is required to be consistent with originating from a PV. The vector from the corresponding PV to the decay vertex of the $B^+$ is required to be closely aligned with the momentum vector of the $B^+$ candidate: the opening angle $\phi$ between them must satisfy $\cos\phi > 0.999$. To ensure a clean separation between the $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ mass peaks in the $J/\psi\pi^+$ mass spectrum, the decay angle $\theta_h$, defined as the angle between the momentum of the kaon or pion in the $B^+$ rest frame and the $B^+$ momentum in the laboratory frame, is required to satisfy $\cos\theta_h < 0$ [8].

The $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ candidates passing the preselection are filtered using the output of a boosted decision tree (BDT) [21, 22] to further suppress combinatorial background. The BDT uses kinematic and topological variables to discriminate between signal and background. These include the impact parameters of the final-state tracks with respect to the PV, as well as those of the $J/\psi$ and the $B^+$ candidates, the $p_{\rm T}$ of the final-state hadron and the $J/\psi$ and $B^+$ candidates, and the decay-length and vertex-fit $\chi^2$ of the $B^+$ candidate. Given the similarity of their kinematic distributions, the same BDT classifier is used to select both decays. The BDT is trained using a simulated sample of $B^+ \to J/\psi\pi^+$ decays and a background sample consisting of candidates from the data sample passing the $B^+ \to J/\psi\pi^+$ preselection with invariant mass in the range 5500–5700 MeV/$c^2$.

Particle identification (PID) criteria are applied to select pion and kaon candidates, with the two hypotheses being mutually exclusive. The requirements on the BDT response



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and PID are chosen to maximise the figure of merit for the decay $B^+ \to J/\psi\pi^+$, defined as $N_\pi/\sqrt{N_{\rm tot}}$, where $N_{\rm tot}$ is the total number of $B^+ \to J/\psi\pi^+$ candidates within $\pm 3$ times the mass resolution around the known $B^+$ mass. Here $N_\pi$ refers to the $B^+ \to J/\psi\pi^+$ signal yield and is estimated to be $(N_{\rm tot} - N_{\rm comb})/(1 + 1/(r_{\rm eff}\mathcal{R}_{\pi/K}))$, where the value of $\mathcal{R}_{\pi/K}$ is given in eq. (1.1), $N_{\rm comb}$ is the number of combinatorial background events in the $B^+ \to J/\psi\pi^+$ signal region extrapolated from the region 5340–5580 MeV/$c^2$ passing the PID selection, and $r_{\rm eff}$ is the ratio of the efficiencies for $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ events to pass the $B^+ \to J/\psi\pi^+$ selection and fall in the signal window, estimated from simulation. After this optimisation, the BDT rejects more than 85% of the combinatorial background and retains around 92% of $B^+ \to J/\psi h^+$ events, where $h = \pi, K$. The particle identification requirement has an efficiency of about 97% for $B^+ \to J/\psi\pi^+$ and 69% for $B^+ \to J/\psi K^+$. The fraction of events in which more than one candidate passes the selection is negligible.

## 4 Signal yield determination

The signal yields $N_{J/\psi h}$ and raw charge asymmetries $A^{\rm raw}_{J/\psi h}$ of the two decay modes are determined from independent unbinned extended maximum likelihood fits to the invariant mass distributions of $B^+ \to J/\psi h^+$ and $B^- \to J/\psi h^-$. Denoting the signal yield for $B^\pm \to J/\psi h^\pm$ by $N_{J/\psi h^\pm}$, $N_{J/\psi h}$ is the sum of $B^- \to J/\psi\pi^-$ and $B^+ \to J/\psi\pi^+$, and $A^{\rm raw}_{J/\psi h}$ is defined as

$$A^{\rm raw}_{J/\psi h} = \frac{N_{J/\psi h^-} - N_{J/\psi h^+}}{N_{J/\psi h^-} + N_{J/\psi h^+}}. \tag{4.1}$$

The fits use $B^+ \to J/\psi\pi^+$ candidates in the range 5000–5600 MeV/$c^2$ and $B^+ \to J/\psi K^+$ candidates in the range 5000–5700 MeV/$c^2$. The $B^+$ and $B^-$ samples are fitted simultaneously, as shown in figures 2 and 3. Table 1 summarizes the fit results for the parameters of interest. In each fit, the signal shape is modelled by a Hypatia function [23]. The most probable value and the resolution of the Hypatia function are allowed to vary in the fit, while the tail parameters are fixed to values determined from fits to simulated events. The hadron misidentification background in the $B^+ \to J/\psi\pi^+$ sample, arising from $B^+ \to J/\psi K^+$ decays in which the kaon is misidentified as a pion, is described by a double-sided Crystal Ball (DSCB) function whose parameters, except for the most probable value and the core width, are fixed to values determined from fits to simulated events. The misidentification background due to $B^+ \to J/\psi\pi^+$ decays in which the pion is misidentified as a kaon is neglected in the baseline fit; a systematic uncertainty due to this assumption is assigned, as discussed in section 6. The combinatorial background is modelled by an exponential function whose shape parameter is left free in the fit. The background due to partially reconstructed $B$-meson decays such as $B \to J/\psi h\pi$ is described by an ARGUS function [24] convolved with a Gaussian function, with all parameters allowed to vary in the fit. Contributions from the highly suppressed $B^+ \to K^+\mu^+\mu^-$ [4] and $B^+ \to \pi^+\mu^+\mu^-$ [25] decays are negligible.



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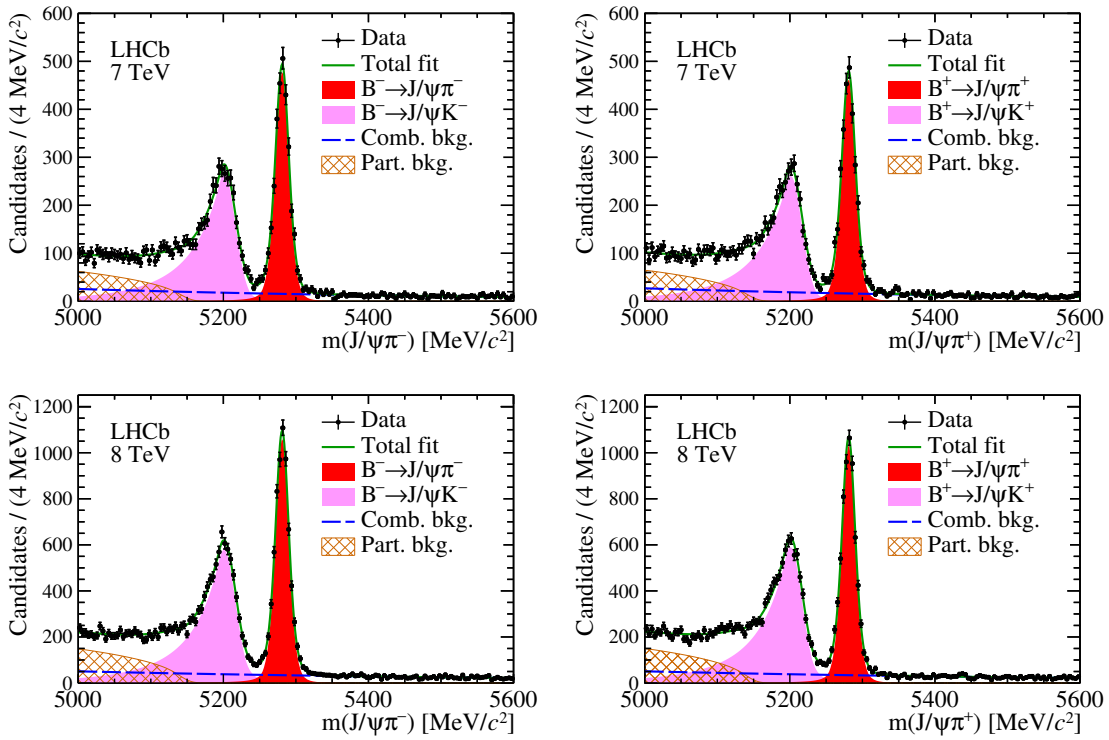


**Figure 2**. Invariant mass distributions of (left) $B^- \to J/\psi\pi^-$ and (right) $B^+ \to J/\psi\pi^+$ candidates with the result of the fit superimposed, for data collected at (top) 7 TeV and (bottom) 8 TeV.

| | 7 TeV | 8 TeV |
|---|---|---|
| $N_{J/\psi\pi}$ | 6011 ± 89 | 13 103 ± 130 |
| $N_{J/\psi K}$ | 107 783 ± 332 | 243 119 ± 499 |
| $A^{\rm raw}_{J/\psi\pi}$ | $(1.64 \pm 1.39) \times 10^{-2}$ | $(1.35 \pm 0.94) \times 10^{-2}$ |
| $A^{\rm raw}_{J/\psi K}$ | $(-1.65 \pm 0.31) \times 10^{-2}$ | $(-1.27 \pm 0.20) \times 10^{-2}$ |

**Table 1**. Signal yields and raw charge asymmetries determined from the fits, which are described in the text. The uncertainties are statistical.

## 5 Efficiency corrections

The ratio of the $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ branching fractions is measured separately for the 7 and 8 TeV samples, and is calculated as

$$\mathcal{R}_{\pi/K} = \frac{N_{J/\psi\pi}}{N_{J/\psi K}} \times \frac{\varepsilon_{J/\psi K}}{\varepsilon_{J/\psi\pi}}, \tag{5.1}$$

where $\varepsilon_{J/\psi\pi}$ and $\varepsilon_{J/\psi K}$ denote the total efficiencies of selecting the two modes, each taking into account the geometrical acceptance of the detector, the trigger, the reconstruction and preselection, the hadron PID, the BDT selection and the fiducial selection. The hadron PID efficiencies are determined using $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ calibration data [26]. Kaons and pions in the calibration samples are weighted to reproduce the momentum and pseu-



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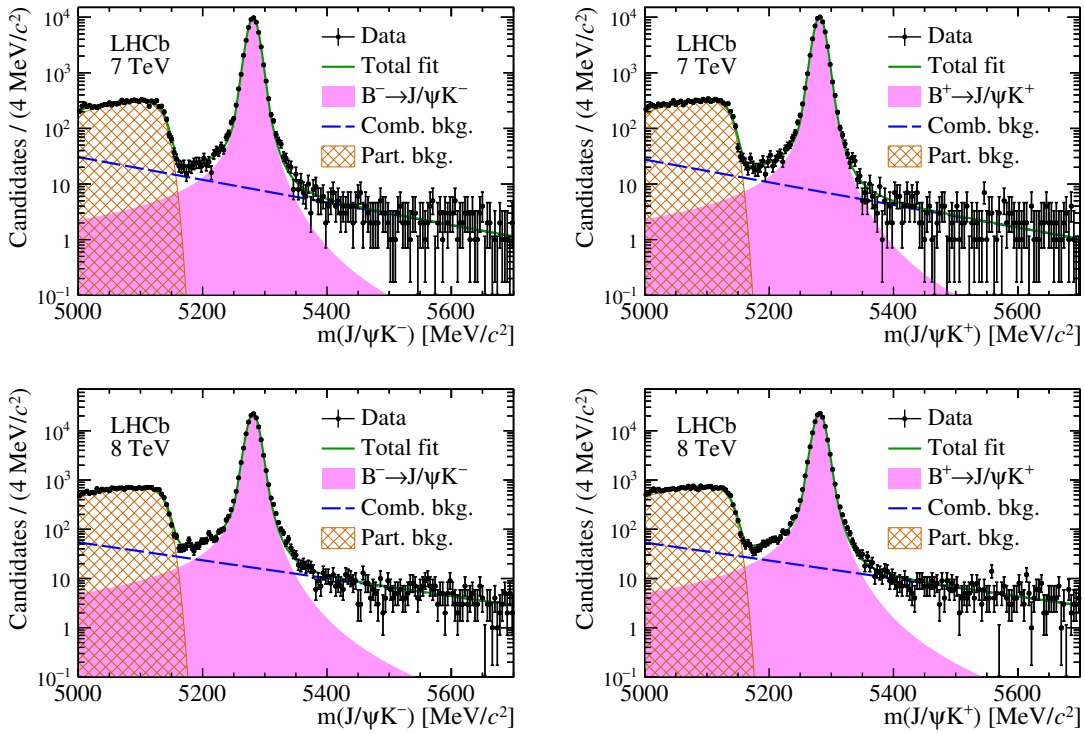


**Figure 3**. Invariant mass distributions of (left) $B^- \to J/\psi K^-$ and (right) $B^+ \to J/\psi K^+$ candidates with the result of the fit superimposed, for data collected at (top) 7 TeV and (bottom) 8 TeV, where the $B^\pm \to J/\psi \pi^\pm$ contributions are neglected.

dorapidity distributions of those from $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi \pi^+$ decays. All other efficiencies are estimated using simulated signal events. The simulated events are weighted such that their kinematic distributions match those of the background-subtracted data, which is obtained using the *sPlot* technique [27]. The efficiency ratio, $\varepsilon_{J/\psi\pi}/\varepsilon_{J/\psi K}$, is estimated to be $1.43 \pm 0.01$ for the $7\,TeV$ data and $1.42 \pm 0.01$ for $8\,TeV$, with the difference from unity being mainly due to the PID selections for the two decays.

The difference in *CP* asymmetries of $B^+ \to J/\psi \pi^+$ and $B^+ \to J/\psi K^+$ is calculated as

$$\begin{aligned} \Delta\mathcal{A}^{\rm CP} &= \Delta A^{\rm raw} - \Delta A^{\rm eff} \,, \\ \Delta A^{\rm raw} &\equiv A^{\rm raw}_{J/\psi\pi} - A^{\rm raw}_{J/\psi K} \,, \\ \Delta A^{\rm eff} &\equiv A^{\rm eff}_{J/\psi\pi} - A^{\rm eff}_{J/\psi K} \,, \end{aligned} \tag{5.2}$$

where $A^{\rm eff}_{J/\psi\pi}$ and $A^{\rm eff}_{J/\psi K}$ are the efficiency asymmetries between $B^-$ and $B^+$ decays. The asymmetry difference $\Delta A^{\rm eff}$ arises from the particle detection efficiency, hadron PID, BDT selection and fiducial selection. The main sources of asymmetry are the detection efficiency and hadron PID, as described below.

The PID efficiency asymmetries of $B^+ \to J/\psi \pi^+$ and $B^+ \to J/\psi K^+$ are estimated separately using the $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ calibration sample mentioned above, and their difference is taken as a contribution to $\Delta A^{\rm eff}$. The average detection asymmetry between $\pi^-$ and $\pi^+$ in $B^+ \to J/\psi \pi^+$ is denoted $A^{\rm det}_\pi$, and that between $K^-$ and $K^+$ in



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$B^+ \to J/\psi K^+$ is likewise denoted $A_K^{\rm det}$. Following the method in ref. [28], the difference $A_\pi^{\rm det} - A_K^{\rm det}$ can be approximated by the combined detection asymmetry between $\pi^- K^+$ and $\pi^+ K^-$, denoted $A_{\pi\overline{K}}^{\rm det}$, which is calculated as

$$A_\pi^{\rm det} - A_K^{\rm det} \approx A_{\pi\overline{K}}^{\rm det} = A^{\rm raw}_{D^-\to K^+\pi^-\pi^-} - A^{\rm raw}_{D^-\to K^0_{\rm S}\pi^-} + A^{\rm det}_{K^0_{\rm S}} \,. \tag{5.3}$$

Here $A^{\rm raw}_{D^-\to K^+\pi^-\pi^-}$ and $A^{\rm raw}_{D^-\to K^0_{\rm S}\pi^-}$ are the raw charge asymmetries measured in the decays $D^- \to K^+\pi^-\pi^-$ and $D^- \to K^0_{\rm S}\pi^-$. The $D^\mp$ production asymmetry cancels in the difference between the two raw asymmetries, and the $CP$ asymmetries in Cabibbo-favoured charm decays are assumed to be negligible. The $D^- \to K^+\pi^-\pi^-$ decays are weighted to match the distributions of $p_{\rm T}$ and rapidity ($y$) of kaons in the $B^+ \to J/\psi K^+$ decays. The $D^- \to K^0_{\rm S}\pi^-$ decays are then weighted to match the kinematic distributions of the $D^- \to K^+\pi^-\pi^-$ sample such that the $p_{\rm T}$ and $y$ distributions of the $D^-$ agree between the two channels, as do the $p_{\rm T}$ distributions of the $\pi^-$ (with one pion chosen at random in the case of $D^- \to K^+\pi^-\pi^-$). The term $A^{\rm det}_{K^0_{\rm S}}$ is a small correction for the effects of $CP$ violation in $K^0$–$\overline{K}^0$ mixing and the different interaction cross-sections of $K^0$ and $\overline{K}^0$ with the detector material [29]. The asymmetry $A_{\pi\overline{K}}^{\rm det}$ is evaluated to be $(1.10 \pm 0.22) \times 10^{-2}$ and $(0.77 \pm 0.10) \times 10^{-2}$ for the 7 and $8\,TeV$ data, respectively. The overall difference in efficiency asymmetry, $\Delta A^{\rm eff}$, is estimated to be $(1.37 \pm 0.56) \times 10^{-2}$ for the $7\,TeV$ data, and $(0.84 \pm 0.43) \times 10^{-2}$ for $8\,TeV$.

## 6 Systematic uncertainties

The data-taking conditions were different for the 7 and $8\,TeV$ data, and therefore the systematic uncertainties, summarised in table 2, are computed separately for the two samples. The relative uncertainties are quoted for the $\mathcal{R}_{\pi/K}$ measurement and absolute uncertainties are quoted for the $\Delta\mathcal{A}^{\rm CP}$ measurement. The systematic uncertainties can be divided into two groups, either associated with the mass fit or with the efficiency. For each systematic uncertainty associated with the mass fit, a fit with an alternative model is performed and the differences in the mean values of $\mathcal{R}_{\pi/K}$ and $\Delta\mathcal{A}^{\rm CP}$ are taken as the corresponding systematic uncertainties. The alternative fits are performed with the same sets of parameters floating or fixed as in nominal fit. In each case, the uncertainties are quoted separately for the 7 and $8\,TeV$ data.

The baseline signal model is a Hypatia function. Changing this to a histogram representing the simulated signal mass distribution convolved with a Gaussian function, to correct for mismatch in resolution between data and simulation, leads to relative uncertainties of 0.39% and 0.25% for $\mathcal{R}_{\pi/K}$ for the 7 and 8 TeV data and absolute uncertainties of $0.03 \times 10^{-2}$ and less than $0.01 \times 10^{-2}$ for $\Delta\mathcal{A}^{\rm CP}$.

The baseline model for the misidentification background in the $B^+ \to J/\psi\pi^+$ sample is a DSCB function with tail parameters obtained from the simulation. Alternative models are constructed by varying the tail parameter values to match those expected for different pion selection requirements, or by using a histogram convolved with a Gaussian function as was done for the signal model. The results from different alternative models are summed in



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quadrature. The resulting relative systematic uncertainties on $\mathcal{R}_{\pi/K}$ are 0.44% and 0.38%, and the estimated systematic uncertainties on $\Delta\mathcal{A}^{\rm CP}$ are $0.01 \times 10^{-2}$ and $0.02 \times 10^{-2}$.

The most probable values and the resolution parameters of the signal and misidentification background models are assumed to be the same for $B^+$ and $B^-$ decays in the baseline fits. Treating the parameters separately for $B^+$ and $B^-$ decays leads to differences (taken as estimates of the associated uncertainties) of $0.04\times10^{-2}$ and $0.05\times10^{-2}$ for $\Delta\mathcal{A}^{\rm CP}$ and 0.04% and 0.02% for $\mathcal{R}_{\pi/K}$.

The baseline model for the combinatorial background is an exponential function. Adding a linear component to this model shifts $\mathcal{R}_{\pi/K}$ by 0.52% and 0.20%, and changes $\Delta\mathcal{A}^{\rm CP}$ by $0.04 \times 10^{-2}$ and $0.01 \times 10^{-2}$.

The baseline fits are performed in mass ranges above $5000\,\mathrm{MeV}/c^2$, where contamination from the partially reconstructed background is expected up to $5150\,\mathrm{MeV}/c^2$. The alternative fits are performed in narrower ranges starting from $5150\,\mathrm{MeV}/c^2$, where partially reconstructed background can be neglected. The value of $\mathcal{R}_{\pi/K}$ is found to change by 0.20% and 0.33%, and that of $\Delta\mathcal{A}^{\rm CP}$ by $0.04 \times 10^{-2}$ and $0.01 \times 10^{-2}$. Systematic uncertainties equal to these shifts are assigned.

The PID efficiencies are calibrated using $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays selected without applying hadron PID requirements. The efficiency depends on the momentum and pseudorapidity of the track and the track multiplicity in the event, and the calibration is therefore done in bins of those variables. The choice of binning necessarily involves a compromise between the granularity and statistical uncertainty of individual bins. Systematic uncertainties due to the limited number of kinematic bins are evaluated by doubling or halving the number of bins and recalculating the average efficiencies. The resulting deviations from the baseline results are taken as the systematic uncertainties: 0.39% and 0.46% for $\mathcal{R}_{\pi/K}$, and $0.06 \times 10^{-2}$ and $0.01 \times 10^{-2}$ for $\Delta\mathcal{A}^{\rm CP}$.

The ratio of BDT efficiencies of the decays $B^+ \to J/\psi\,\pi^+$ and $B^+ \to J/\psi\,K^+$ is estimated with simulated samples of signal events, which are weighted to remove differences in the distributions of the BDT input variables between the simulation and data. Relative systematic uncertainties of 0.01% and 0.02% are assigned to $\mathcal{R}_{\pi/K}$, to account for statistical uncertainties on the weights used in the efficiency calculation.

The ratio of trigger efficiencies of the decays $B^+ \to J/\psi\,\pi^+$ and $B^+ \to J/\psi\,K^+$ is determined from simulation and validated with a control sample of $J/\psi \to \mu^+\mu^-$ decays [12]. Relative differences of 0.33% and 0.38% are found between the values of this ratio estimated with data and with simulation, which are taken as the corresponding systematic uncertainties on $\mathcal{R}_{\pi/K}$.

Samples of $D^+$ decays are used to determine the difference between the kaon and pion detection efficiency asymmetries. However, the kinematic distributions of the pions and kaons in the $D^+$ samples may differ from those of the signal $B^+ \to J/\psi\,h^+$ samples, and the efficiency asymmetries may vary with the particle kinematics. To assess the scale of this effect, samples of $D^+ \to K^-\pi^+\pi^+$ events are weighted such that the distribution of the momentum of the kaon matches that of $B^+ \to J/\psi\,K^+$, leading to a pion detection asymmetry of $0.12 \times 10^{-2}$ for both 7 and $8\,TeV$ data. This is taken as a systematic uncertainty.



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| Sources | $\mathcal{R}_{\pi/K}$ (7 TeV) [%] | $\mathcal{R}_{\pi/K}$ (8 TeV) [%] | $\Delta\mathcal{A}^{\rm CP}$ (7 TeV) [$\times 10^{-2}$] | $\Delta\mathcal{A}^{\rm CP}$ (8 TeV) [$\times 10^{-2}$] |
|---|---|---|---|---|
| Signal model | 0.39 | 0.25 | 0.03 | — |
| Mis-ID background | 0.44 | 0.38 | 0.01 | 0.02 |
| $B^{\pm}$ parameters | 0.04 | 0.02 | 0.04 | 0.05 |
| Comb. background | 0.52 | 0.20 | 0.04 | 0.01 |
| Part. reco. background | 0.20 | 0.33 | 0.04 | 0.01 |
| PID efficiency | 0.39 | 0.46 | 0.06 | 0.01 |
| BDT efficiency | 0.01 | 0.02 | — | — |
| Trigger efficiency | 0.33 | 0.38 | — | — |
| Detection asymmetry | — | — | 0.12 | 0.12 |
| $B^{\pm}$ prod. asymmetry | — | — | 0.02 | 0.04 |
| $K/\pi$ interaction | 0.03 | 0.03 | — | — |
| Total | 1.01 | 0.83 | 0.15 | 0.14 |

**Table 2**. Relative systematic uncertainties (%) for $\mathcal{R}_{\pi/K}$ and absolute systematic uncertainties ($\times 10^{-2}$) for $\Delta\mathcal{A}^{\rm CP}$. The uncertainties are quoted separately for the 7 and 8 TeV data. The dashes indicate negligible uncertainties (zero after rounding to two decimal places).

The production asymmetry of $B^+$ mesons is a function of the $B^+$ kinematics. This dependence cancels in the observables considered, provided that $B^+ \to J/\psi\,\pi^+$ and $B^+ \to J/\psi\,K^+$ decays have the same kinematic distributions. Good agreement is found between the $p_{\rm T}$ distributions of the decays $B^+ \to J/\psi\,\pi^+$ and $B^+ \to J/\psi\,K^+$, but not for the rapidity distributions. The deviations of the $B^+$ production asymmetry with and without the weights that match the rapidity distribution in the $B^+ \to J/\psi\,\pi^+$ sample to that of the $B^+ \to J/\psi\,K^+$ decay, are $0.02 \times 10^{-2}$ and $0.04 \times 10^{-2}$, which are taken as the systematic uncertainties on $\Delta\mathcal{A}^{\rm CP}$.

A systematic uncertainty of 0.03% on $\mathcal{R}_{\pi/K}$ is assigned to account for imperfect simulation of hadron interactions in the detector, determined from the known interaction cross-sections for pions and kaons and assuming an uncertainty of 10% in the material budget of the detector. Summing all of the above contributions in quadrature, the relative systematic uncertainty on $\mathcal{R}_{\pi/K}$ is 1.01% for the $7\,TeV$ sample and 0.83% for $8\,TeV$ and the absolute uncertainty on $\Delta\mathcal{A}^{\rm CP}$ is $0.15 \times 10^{-2}$ for $7\,TeV$ and $0.14 \times 10^{-2}$ for $8\,TeV$.

## 7 Results and conclusion

Using the estimated signal yields, efficiency ratios, raw charge asymmetries and efficiency asymmetries, the ratio of branching fractions and difference in *CP* asymmetries of the decay modes $B^+ \to J/\psi\,\pi^+$ and $B^+ \to J/\psi\,K^+$ are measured to be

$$\mathcal{R}_{\pi/K} = \begin{cases} (3.90 \pm 0.06 \pm 0.04) \times 10^{-2} & \text{for } 7\,TeV \\ (3.79 \pm 0.04 \pm 0.03) \times 10^{-2} & \text{for } 8\,TeV\,, \end{cases}$$

$$\Delta\mathcal{A}^{\rm CP} = \begin{cases} (1.92 \pm 1.53 \pm 0.15) \times 10^{-2} & \text{for } 7\,TeV \\ (1.77 \pm 1.05 \pm 0.14) \times 10^{-2} & \text{for } 8\,TeV\,. \end{cases}$$



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Here the first uncertainties are statistical, which are uncorrelated between the 7 and 8 $TeV$ results, and the second uncertainties are systematic, which are taken to be fully correlated between the 7 and 8 $TeV$ results. The average of the 7 and 8 TeV results, weighting each according to its statistical uncertainty, are

$$\mathcal{R}_{\pi/K} = (3.83 \pm 0.03 \pm 0.03) \times 10^{-2},$$
$$\Delta\mathcal{A}^{\rm CP} = (1.82 \pm 0.86 \pm 0.14) \times 10^{-2}.$$

The LHCb collaboration has recently reported the *CP* asymmetry $\mathcal{A}^{\rm CP}(B^+ \to J/\psi K^+) = (0.09 \pm 0.27 \pm 0.07) \times 10^{-2}$ [9], where the first uncertainty is statistical and the second systematic. The sample analysed in ref. [9] is statistically correlated with that used in this analysis, but the correlation is only partial due to the use of different trigger requirements. The correlation coefficient between the statistical uncertainties of the two analyses is found to be $-4.8\%$. The systematic uncertainty on $\mathcal{A}^{\rm CP}(B^+ \to J/\psi K^+)$ is taken to be uncorrelated with that on the $\Delta\mathcal{A}^{\rm CP}$ measurement. Therefore the *CP* asymmetry in the decay $B^+ \to J/\psi\pi^+$ is

$$\mathcal{A}^{\rm CP}(B^+ \to J/\psi\pi^+) = \Delta\mathcal{A}^{\rm CP} + \mathcal{A}^{\rm CP}(B^+ \to J/\psi K^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}.$$

This is the most precise determination of $\mathcal{A}^{\rm CP}(B^+ \to J/\psi\pi^+)$ to date, and it supersedes the previous LHCb result [8]. The $\mathcal{R}_{\pi/K}$ and $\mathcal{A}^{\rm CP}(B^+ \to J/\psi\pi^+)$ measurements can be combined with measurements of decay rates and *CP* asymmetries in other $b \to c\bar{c}d$ decays, such as $B^0 \to J/\psi\pi^0$, to understand the effect of loop contributions in $b \to c\bar{c}s$ decays using SU(3) flavour symmetry [2, 3].

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